UNCLASSIFIED

CONFIDENTIAL

Copy
RM L57F21

426

NACA RM L57F21

N63-12521
Code-1



RESEARCH MEMORANDUM

THE DESIGN AND CASCADE TESTS OF FREE-STREAMLINE AND FULL-CONTOUR 160° TURNING SUPERSONIC-TURBINE-BLADE SECTIONS

By Willard R. Westphal

Langley Aeronautical Laboratory
Langley Field, Va.

OTS PRICE
XEROX $ 2.60 ph
MICROFILM $ 0.92 mf

CLASSIFICATION CHANGED TO
UNCLASSIFIED - AUTHORITY
NASA - EFFECTIVE DATE
SEPTEMBER 14, 1962

CLASSIFIED DOCUMENT

This material contains information affecting the National Defense of the United States within the meaning of the espionage laws, Title 18, U.S.C., Secs. 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON
August 16, 1957

CONFIDENTIAL

UNCLASSIFIED

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

THE DESIGN AND CASCADE TESTS OF FREE-STREAMLINE AND FULL-CONTOUR 160° TURNING SUPERSONIC-TURBINE-BLADE SECTIONS

By Willard R. Westphal

SUMMARY

The flow characteristics of two supersonic-impulse-turbine-blade sections designed for a turning angle of 160° have been studied. One section was of the full-contour vortex-flow type having a convex-surface design Mach number equal to the entering Mach number of 1.57 and a concave-surface design Mach number of 0.8. The other section had the same concave surface but a large part of the convex surface was cut away and a free streamline was left as the boundary of the flow in the passage.

The full-contour blades had a recovery factor of 0.83 at an entering Mach number of 1.9 and required a variable-geometry tunnel to start supersonic flow in the passage. The free-streamline blades had a recovery factor of 0.73 at an entering Mach number of 1.7 and started supersonically without an increase in Mach number.

INTRODUCTION

Turbines driven by high-pressure gases such as supplied by rocket fuels are being used to furnish shaft power for a variety of uses. Such a powerplant has a very low installed weight and, if only a short operating time is required, the total weight of the powerplant plus fuel will be lower than that of other powerplants.

Since the pressure of the driving gases is very high, a high power extraction per pound of gas is necessary if a reasonable efficiency is to be attained. Many of the applications require only a few hundred horsepower and the gas flow quantities are then so small that a full-annulus-admission turbine would be only a few inches in diameter and would operate at rotational speeds of over 100,000 rpm. In order to increase the diameter and to reduce the rotational speed to more practical values, such

turbines are usually designed for only partial-annulus admission. Partial-admission turbines are inherently less efficient than full-admission ones because of the additional losses associated with the turbine rotor blades entering and leaving the driving gas stream and the windage losses of the blades while out of the stream. Multistage partial-admission turbines would presumably be even less efficient because of the necessity of collecting the gas stream leaving each rotor row.

In order to use full admission in some applications where partial admission would otherwise be required, a very high inlet-air angle is necessary so that the axial velocity would be low. This paper describes the design and cascade tests of two supersonic-turbine blade sections suitable for such applications. The sections were designed for a high turning angle so that a high power extraction could be obtained from a single stage.

SYMBOLS

M	Mach number
p	pressure
R^*	nondimensional radius in vortex field, radius divided by radius at which $M = 1.0$
z	spanwise distance from tunnel wall
β	inlet-air angle, angle between entering flow and a perpendicular to line of blades
δ	angle of floor from horizontal
ν	supersonic property angle, angle through which flow must be turned from $M = 1.0$ to given Mach number
η_l	local recovery factor, $p_{t,l}/p_{t,\infty}$
η_s	section recovery factor of first passage, $\int_{\text{First passage}} \eta_l$

Subscripts:

L	lower or concave surface

UNCLASSIFIED

U	upper or convex surface
t	stagnation conditions
l	local
∞	inlet free stream

DESIGN OF BLADE SECTIONS

Design Conditions

The inlet-air angle β was selected as 80° since this value was as high as was considered practicable. The design of a nozzle that would provide the high swirl required by a rotor at an inlet angle of 80° would require modification to methods presently employed to use radial inflow to increase the tangential velocity component between the nozzle and the rotor.

The turning angle was then selected as 160° on the basis that high power extraction and a small pressure change across the rotor (impulse-type rotor) were desirable. An entering Mach number of 1.57 was used since an existing test section designed for this Mach number was available.

Design Considerations

If it is specified that the blade passage has a large enough throat to pass the starting shock wave of a fixed-geometry upstream nozzle and that the flow is of the vortex type at the throat, reference 1 shows that for the Mach number chosen either the design values of the convex-surface Mach number must be quite high or the blade loading must be comparatively light. The low blade loadings would result in a flow passage that is long in comparison with its width and, hence, would have a large wetted area per unit of mass flow.

Two examples of sections that would just start for an entering Mach number of 1.57, as determined from figure 13 and table I of reference 1, are shown in the following table:

Blade section	Convex surface			Concave surface			$\frac{R^*_U}{R^*_L}$
	ν	M	R*	ν	M	R*	
I	14	1.57	0.7102	4	1.218	0.8532	0.8325
II	27	2.02	0.6137	0	1.000	1.0000	0.6137

The first example has a convex-surface Mach number equal to the entering Mach number and the lowest concave-surface Mach number that will permit the passage to start. The convex-surface radius is not much less than that of the concave surface which means that the width of the flow passage between blades would be small in comparison with its length and which implies a large wetted area per unit of mass flow. In the second example, a greater difference in Mach number for the concave and convex surfaces is chosen which greatly improves the length-width ratio of the flow passage but does so at the expense of the rather high convex-surface Mach number. If the supersonic starting problem were avoided, it would be possible to design a blade section having both low surface Mach numbers and a more favorable length-width ratio of the flow passage. The starting problem is, of course, a very real one for a fixed-geometry cascade tunnel and for the turbine of a gas-turbine powerplant. For turbines driven by an independent source of high-pressure gas, however, it seems likely that some blade configurations that do not start in a cascade tunnel would be acceptable since the inlet-air angle normally varies in the proper manner to assist starting. If the flow in the rotor passage is not supersonic, the torque developed will be low and, hence, the rotational speed will be lower than designed and will result in a higher rotor inlet-air angle which in turn will reduce the width of the stream tube entering each blade passage and, hence, will assist starting.

One of the two blade sections described in this paper was designed to obtain desirable blade configurations and surface Mach numbers at the design condition, and the starting problem was avoided by the use of a simple variable-geometry test section. The second section also has low blade-surface Mach numbers and the starting problem was avoided by eliminating the contracting throat usually required by conventional supersonic blading. The question of the starting behavior of a rotor using either of these sections has not been investigated.

Full-Contour Blade Section

The first blade section, shown in figure 1, was designed to have concentric arcs for the greater part of the concave and convex surfaces of adjacent blades. The design convex-surface Mach number was equal to the entering Mach number of 1.57 and the design concave-surface Mach number was 0.8. The supersonic portion of the concave surface and the whole convex surface were laid out by the characteristic method described in reference 1. The circular portion of the subsonic concave surface was easily determined since vortex flow was assumed and the surface Mach number was specified. These conditions also determine the entering mass flow and, hence, the width of the entering stream tube. The transonic portion between the sonic point and the circular portion was arbitrarily drawn as a smoothly faired line. The leading and trailing edges were modified to incorporate a wedge angle of 8° without changing the concave surface

UNCLASSIFIED

contour (ref. 1). It should be noted that this blade section cannot start at a Mach number of 1.57.

Free-Streamline Blade Section

All of the convex surface of the blades in figure 1 except the leading-edge and trailing-edge wedges has the same local Mach number at design conditions. The pressure is, therefore, the same over the surface and the only force exerted on it is that due to skin friction. It appears, therefore, that much of this surface could be removed without greatly changing the flow pattern. The convex-surface Mach number was, in fact, made equal to the upstream Mach number for this purpose. The free-streamline blade section shown in figure 2 is the same as that of figure 1 except for the removal of part of the convex surface which, thereby, reduces the blade wetted surface and essentially eliminates the throat contraction. The decrease in losses due to skin friction is counteracted by the additional losses due to the turbulence at the free-stream boundary. If the air in the space formerly occupied by the blade were more or less stationary or if it were being continually carried downstream and replaced, it is quite apparent that the free-streamline blades would have greater losses than the full-contour blades because of the larger scale turbulence at the free-streamline interface than at the blade surface. However, since the air is confined to a space that is nearly round, at least as compared with the usual shape of a separated flow bubble of a conventional airfoil, it should be able to rotate as a vortex and, thereby, greatly reduce the difference in velocity across the free streamline. The peripheral velocity of the vortex is such that the energy lost by the vortex due to skin friction along surface AB is transferred from the main stream flow to the vortex flow along the free streamline. For these very high turning angles, the length of boundary AB is small relative to the length of the wetted surface that was removed. Hence, it was considered possible that the free-streamline blades might show lower losses than the full-contour blades. Besides avoiding the supersonic starting problem and reducing the wetted-surface area, the free-streamline blades have these other possible advantages over conventional full-contour blades:

1. The effect of back pressure on torque would be quite different for a turbine having free-streamline blading since the static pressure is propagated upstream through the rotor even though the velocities relative to the rotor are supersonic. This effect may or may not be advantageous, depending on the application.

2. Since the wetted surface available for heat transfer to the blade is less, blade cooling should be easier.

3. The blade taper from root to tip of a rotor blade could be dictated largely by mechanical considerations since the location of the solid-blade boundary to the free streamline is not critical.

APPARATUS AND PROCEDURE

In order to evaluate the relative performance of these two blade sections, an existing 2-inch by 3-inch blowdown-jet test section located in the Gas Dynamics Branch of the Langley Aeronautical Laboratory was used since their turning angle was too great to be accommodated in the Langley 6-inch by 10-inch supersonic cascade tunnel. The test section had no provision for boundary-layer bleedoff and turning-angle measurements but was considered adequate for determining the recovery factor of the two blade sections. The wave patterns were also observed by a schlieren system adjusted for low sensitivity so that the pictures are essentially shadowgraphs.

Figure 3 is a sketch of the test section with one side wall removed and the full-contour blades installed. The angle of the lower floor was adjustable from horizontal to 18° open so that the Mach number entering the blade row could be increased for starting the full-contour blades. The floor angle was set at 18° prior to tunnel operation and was reduced to the minimum setting at which either one or two passages were observed to remain started. The rake was movable both spanwise and streamwise, but all the data presented were taken with it in the streamwise position shown. Spanwise surveys of one-half of the passage were made at two floor angles for each blade section. The two static tubes were 1/2 inch away spanwise from the line of total-pressure tubes. The static orifices were at the same streamwise station as the total-pressure orifices.

This test section did not closely simulate an infinite cascade. The lower floor was always from 2° to 9° open and the expansion waves from the floor hinge line and their reflections produced an appreciable Mach number gradient in the entering flow. The entering Mach numbers reported were found from the inclinations of the Mach line near the entrance to the first passage and are thought to be accurate to ±0.05. The recovery factors reported are from area weighted averages of the total pressure measured by a rake in the first passage. The Mach number ahead of the total-pressure tube was determined by assuming the static tubes measured static pressure ahead of the bow wave of the total-pressure tubes. The rake's total-pressure readings were corrected for the normal shock loss by use of this Mach number.

The entering total pressure was approximately 5 atmospheres for all tests reported. The discharge pressure was atmospheric. Preliminary tests showed that there was no further change in flow pattern upstream of the rake as pressure ratio was increased.

UNCLASSIFIED

The settling-chamber pressure was measured by a calibrated Bourdon type gage. Other pressures were recorded by photographing mercury filled manometer boards.

RESULTS AND DISCUSSION

Full-Contour Blades

Figure 4 is a schlieren photograph of the full-contour blades at a floor angle of 8.4°. This is the lowest floor angle at which both visible passages are started. The Mach number at the entrance of the first passage is about 2.0.

This cascade could not operate at the design entering Mach number of 1.57 because the design incorporated no allowances for boundary-layer effects. These blade sections are particularly inflexible as far as being able to adjust their flow pattern for even small errors in boundary-layer allowance because the passage is very nearly choked when operating at the intended design condition. The sonic line is quite close to the mean radius of the passage and, as pointed out in reference 1, this is approximately the flow condition for maximum possible mass flow. Sections designed for supersonic Mach numbers on both surfaces, but not necessarily capable of starting, would be able to operate closer to or at the design entering Mach number even if the boundary-layer allowance were too small. This, of course, assumes that supersonic flow is established in the blade passage by varying the entering Mach number in some manner.

The oblique shock on the concave side of the leading edge (fig. 4) appears to cause flow separation where it impinges on the convex surface. This shock wave is of finite strength because of the expansion from the floor hinge line. Some of the reflections of these waves fall behind the leading edge; hence, the local incidence angle of the concave side of the leading edge is slightly positive instead of zero. This separation probably contributes a considerable part of the losses and also further decreases the effective throat area.

The section recovery factors are obtained by mechanical integration of the first passages of the curves of figure 5 and are plotted in figure 6. Note that these section recovery factors do not include the mixing loss or all of the friction loss of the first blades since the rake is not downstream of the whole passage (fig. 3). The passage recovery factor is found to be 0.75 by integrating figure 6.

The Mach number at the entrance to the first passage decreased only slightly to about 1.9 as the floor angle was lowered to 5.2°. Figure 7

UNCLASSIFIED

is a schlieren photograph at this floor angle and figures 8 and 6 show the recovery factors. This was the lowest angle at which the first passage was supersonic. There was a detached shock at the entrance of the second passage. The recovery factor increased to 0.83 perhaps because of the lower mixing losses with the flow of the second passage.

Free-Streamline Blades

The cascade of free-streamline blades did not require an increase in floor angle for starting. The flow pattern was the same regardless of whether the operating condition was approached by opening or closing the floor.

Figure 9 is a schlieren photograph of the free-streamline blades at a floor angle of 5.2° and an entering Mach number of about 1.9. These are the conditions at which the full-contour blades had the highest recovery factor, within their range of operation.

The free-streamline blades appear to have a larger boundary layer on the blade surface after the flow has reattached than the full-contour blades had on the same surface. Figure 10 when compared with figure 8 shows that the local recovery factor is less than that for the full-contour blades and that the secondary flow effects are much less (flow more nearly two-dimensional spanwise) or are masked by the turbulence and mixing at the boundary of the vortex. The passage recovery factor from figure 11 is 0.68 or 0.15 lower than that of the full-contour blades.

Figure 12 is a schlieren photograph of the free-streamline blades at a floor angle of 2.3° which is the lowest angle at which the flow was supersonic. The flow pattern is similar to that at a floor angle of 5.2° and figure 13 shows the section recovery factors to be slightly higher. The passage recovery factor from figure 11 is 0.73.

Comparison of Performance

The performance data of the two blade sections are summarized in the following table:

	Full-contour blades		Free-streamline blades	
Floor angle	8.4	5.2	5.2	2.3
Entering Mach number	2.0	1.9	1.9	1.7
Recovery factor	0.75	0.83	0.68	0.73

UNCLASSIFIED

The only other known performance data for blade sections having turning angles comparable to these are presented in reference 1. The recovery factors of four different blade sections designed for a turning angle of 120° were all about 0.88 at an entering Mach number of 1.57.

Two ways to improve the performance of these full-contour blades are apparent. Incorporating a suitable boundary-layer allowance would permit the blades to operate at a lower Mach number. Also, elimination of the shock wave spanning the passage entrance by properly matching the entering Mach number of the blades for best performance and the wave-free Mach number of the tunnel would probably reduce the separation and the losses. These changes should improve the blades' performance but the magnitude of the improvement is, of course, unknown.

The data for the free-streamline blades do not suggest any obvious change that would improve their performance. Their performance should be compared with that of a blade section that would turn the flow 160° and start supersonically at the design Mach number and angle. No such data are available. The recovery factor of these first free-streamline blades is low (0.73) but their other advantages may make them suitable for some applications.

CONCLUSIONS

Two impulse-type turbine blade sections designed for high power extraction and relatively low axial inlet Mach number are described. Both sections were designed for an inlet-air angle of 80° and a relative inlet Mach number of 1.57.

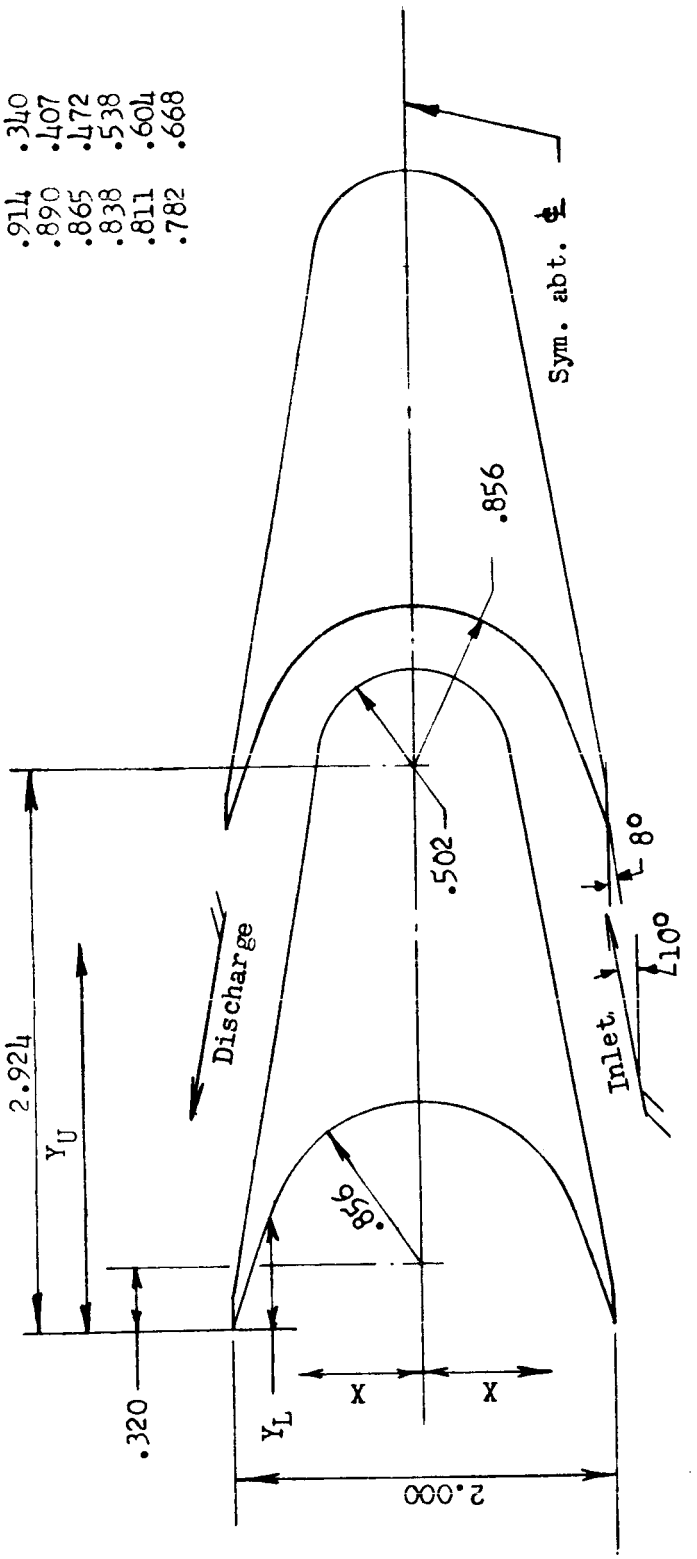
The full-contour blades, which required a variable Mach number nozzle for supersonic starting, could not operate below an entering Mach number of 1.9 because of a lack of boundary-layer growth allowance. For this condition, a passage pressure recovery of 0.83 was measured. The data suggest two possible improvements in the design to permit operation at design inlet Mach numbers. The free-streamline blades, which eliminate the starting problem, although capable of operation at lower Mach number than the full-contour blade, exhibited poorer performance. A pressure recovery of 0.73 was measured at an inlet Mach number of 1.7.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., June 6, 1957.

REFERENCE

1. Boxer, Emanuel, Sterrett, James R., and Wlodarski, John: Application of Supersonic Vortex-Flow Theory to the Design of Supersonic Impulse Compressor- or Turbine-Blade Sections. NACA RM L52B06, 1952.

UNCLASSIFIED



BLADE COORDINATES

X	Y_U	X	Y_L
1.000	0	1.000	0
.994	.179	.989	.063
.495	3.011	.971	.134
		.955	.203
		.935	.272
		.914	.340
		.890	.407
		.865	.472
		.838	.538
		.811	.604
		.782	.668

Figure 1.- Full-contour blade sections. All dimensions are in inches unless otherwise indicated.

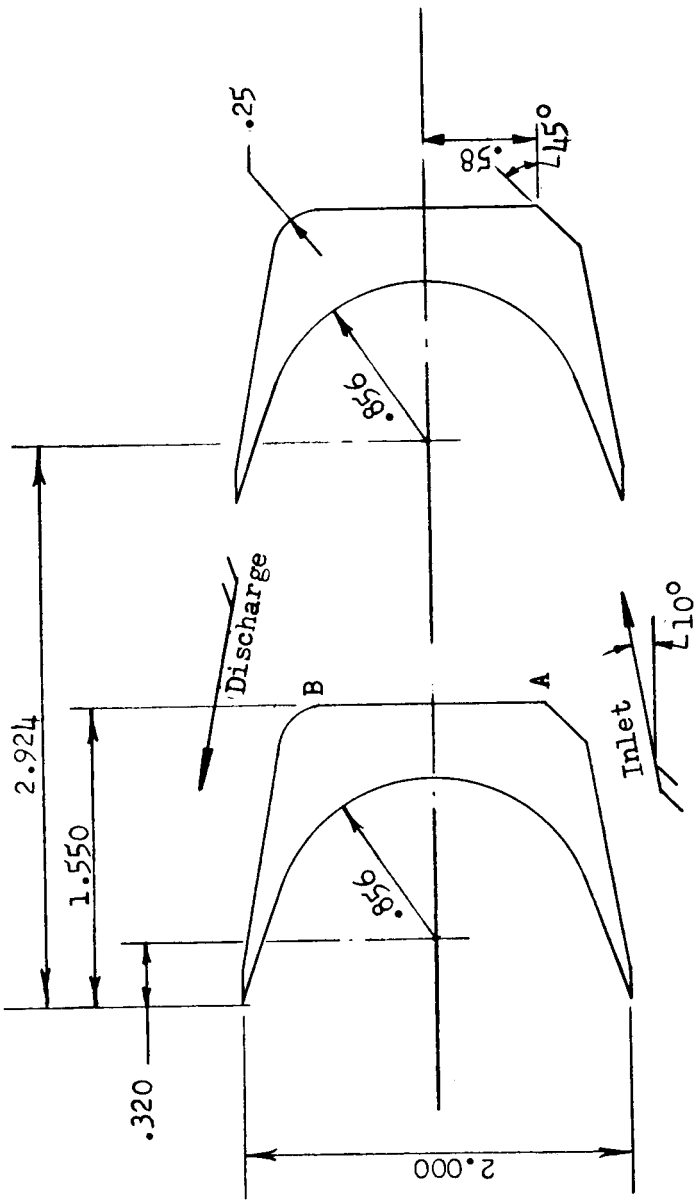


Figure 2.- Free-streamline blade sections. All dimensions are in inches unless otherwise indicated.

UNCLASSIFIED

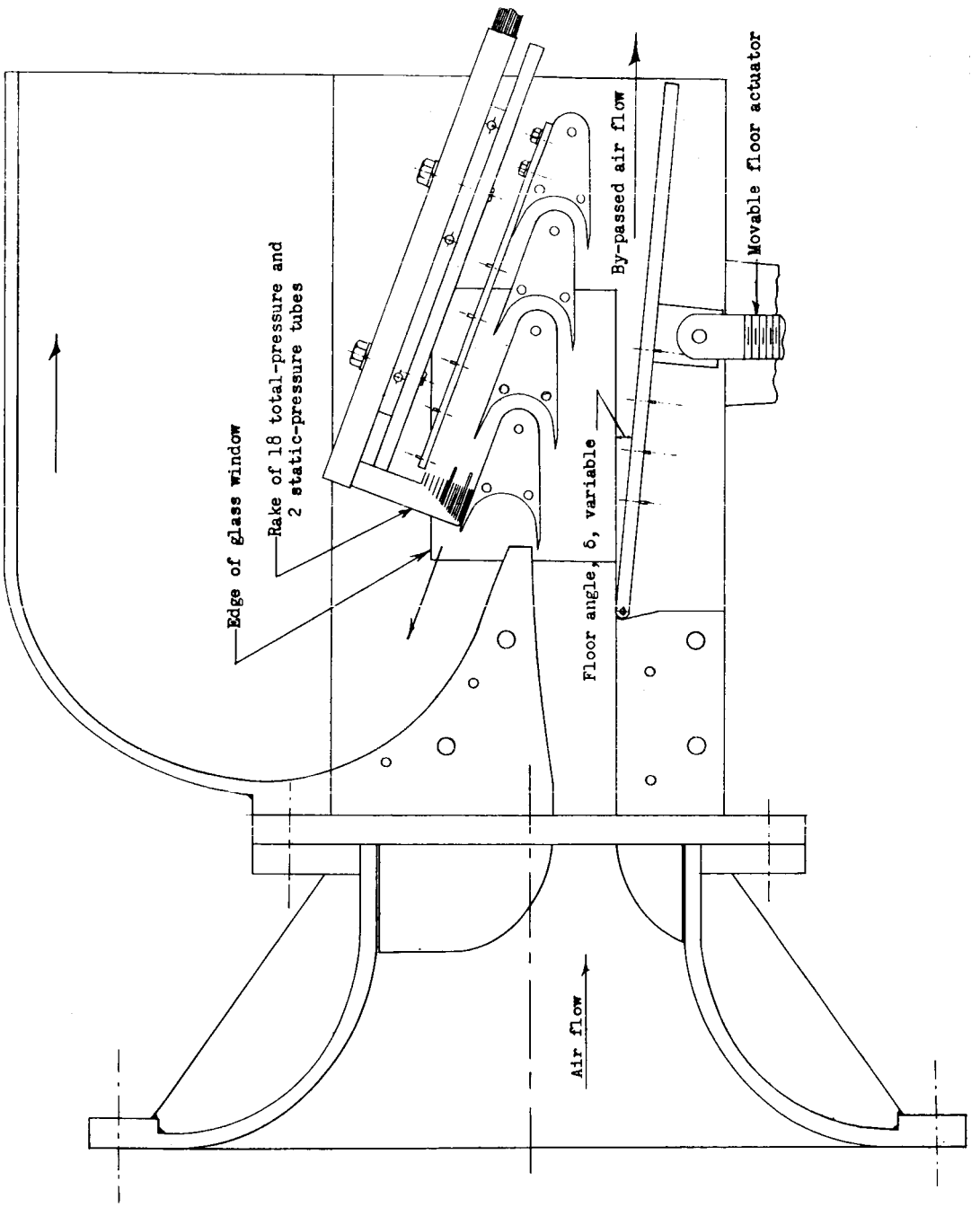
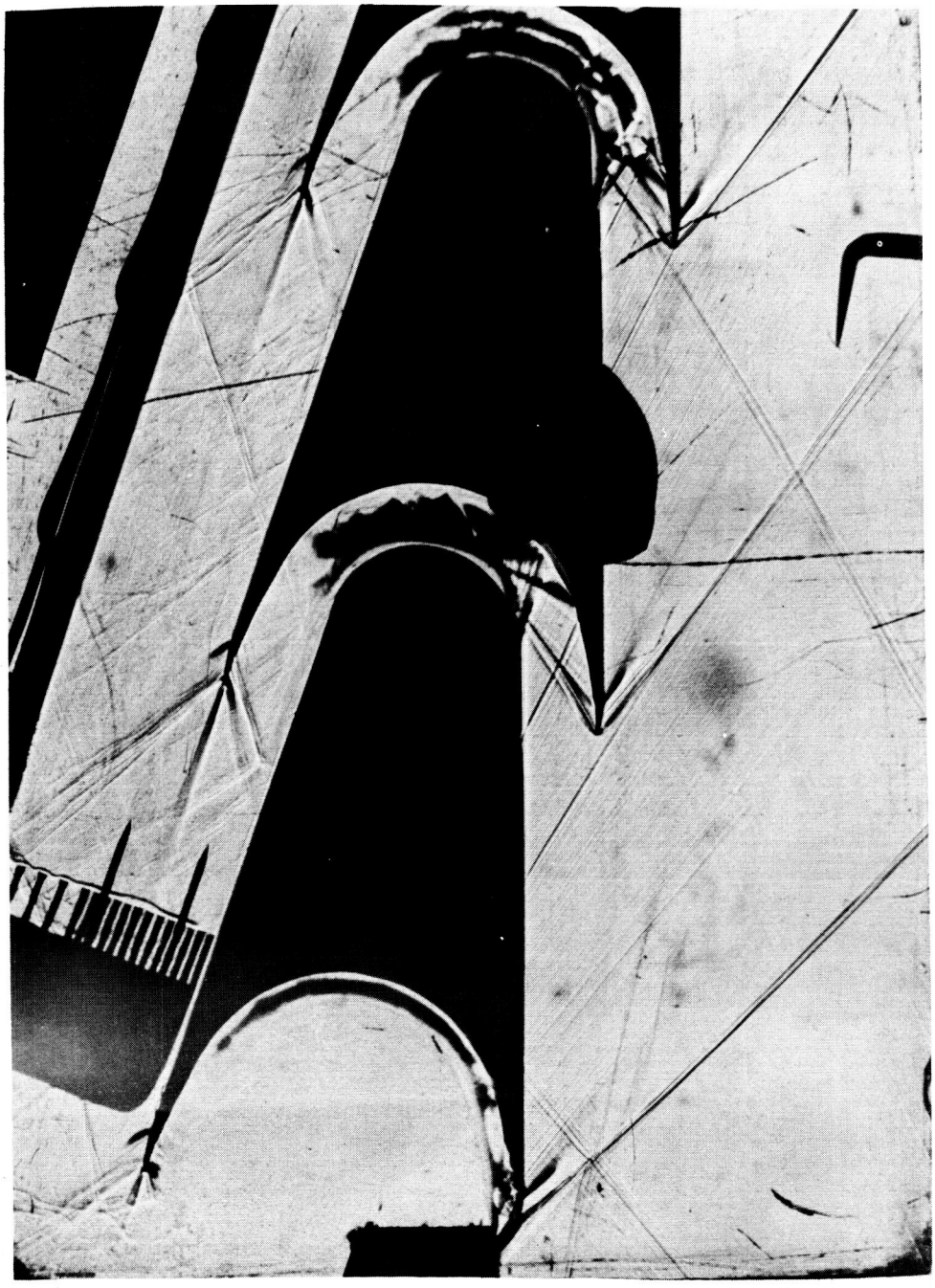


Figure 3.- Sketch of test section with full-contour blade section installed and one wall removed.



L-57-1616

Figure 4.- Schlieren photograph of full-contour blades at a floor angle of 8.4°. Rake is 1.500 inches from tunnel wall.

UNCLASSIFIED

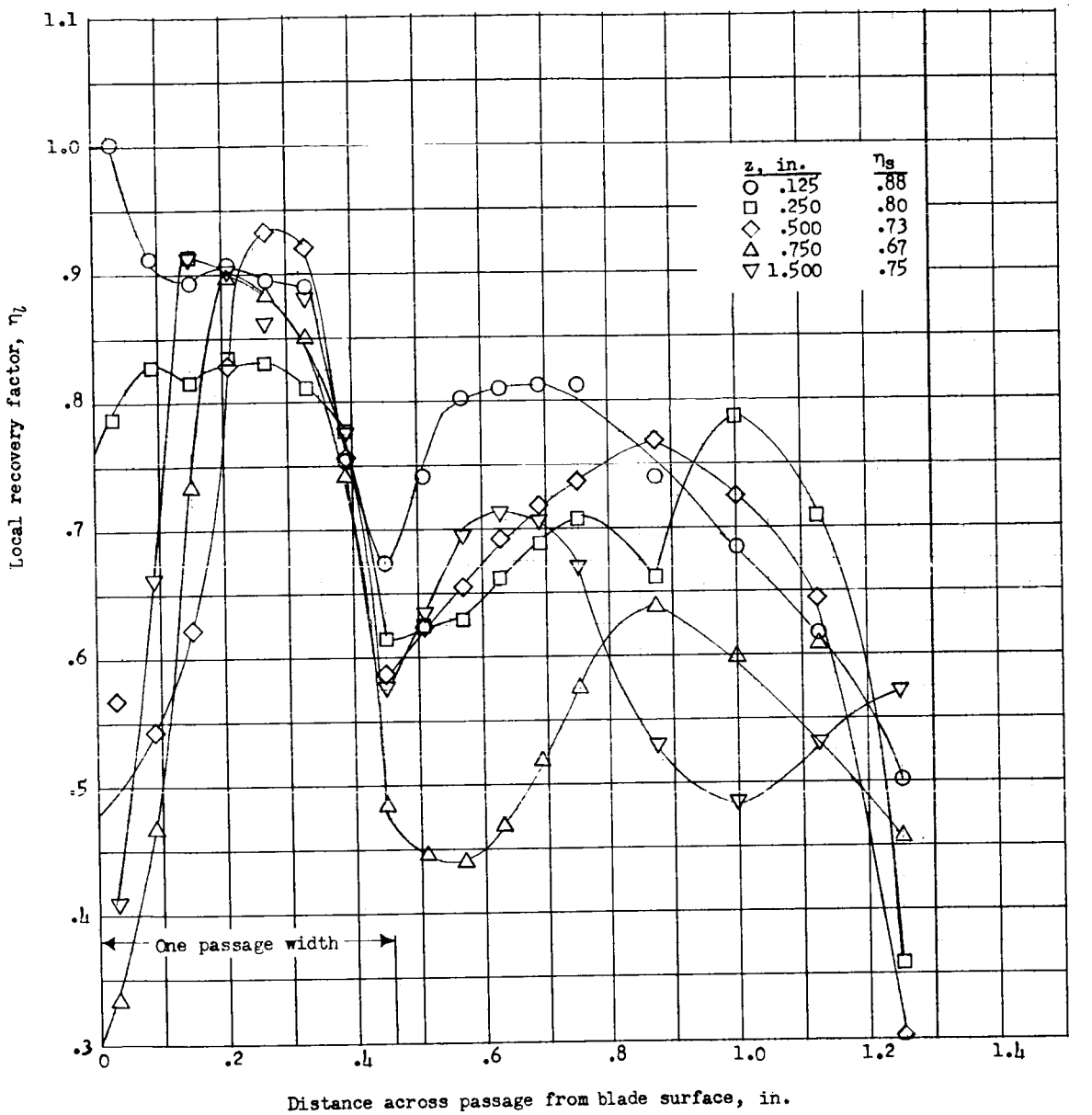


Figure 5.- Local recovery factor for full-contour blades at a floor angle of 8.4°. Both visible passages started.

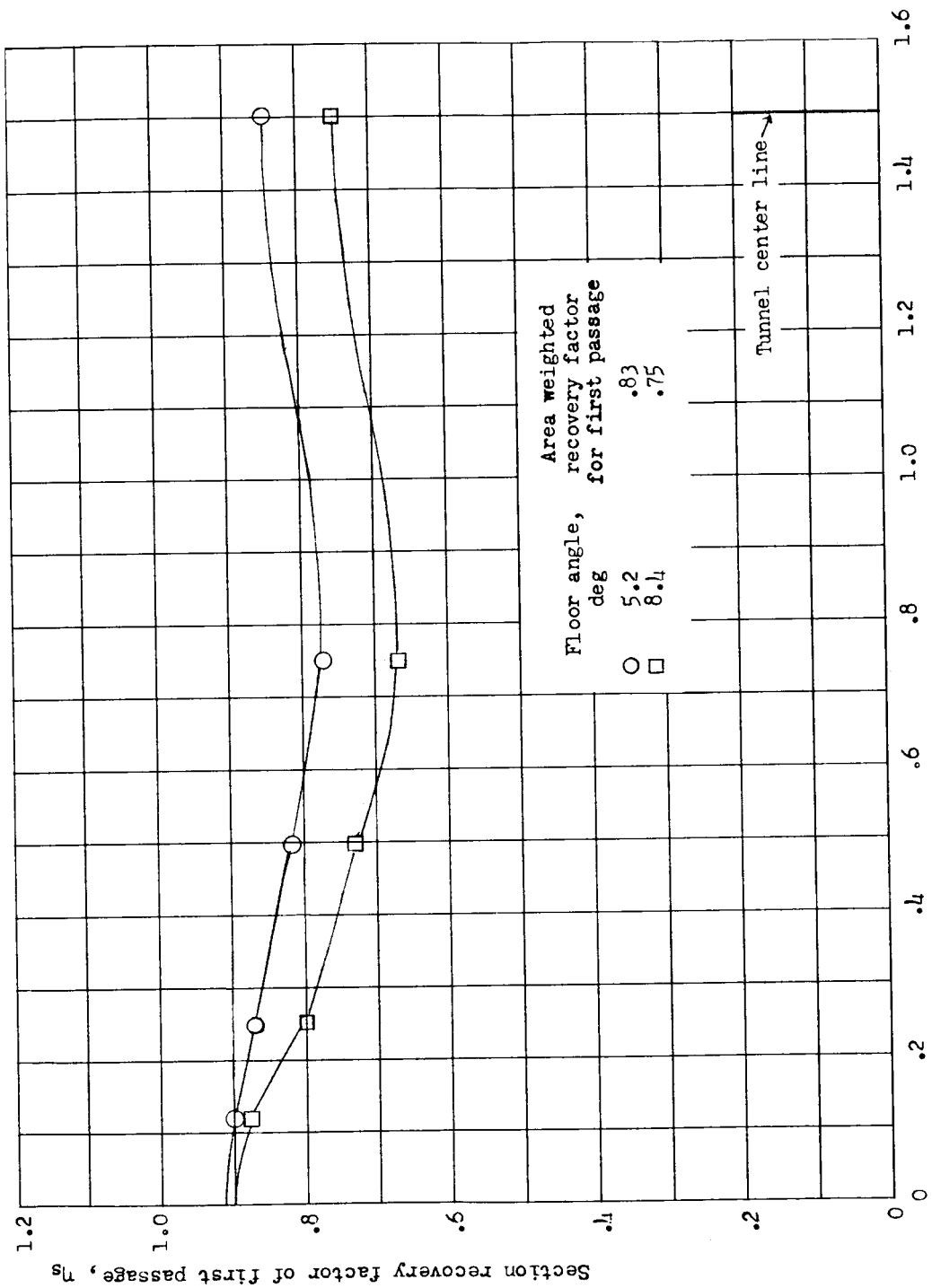
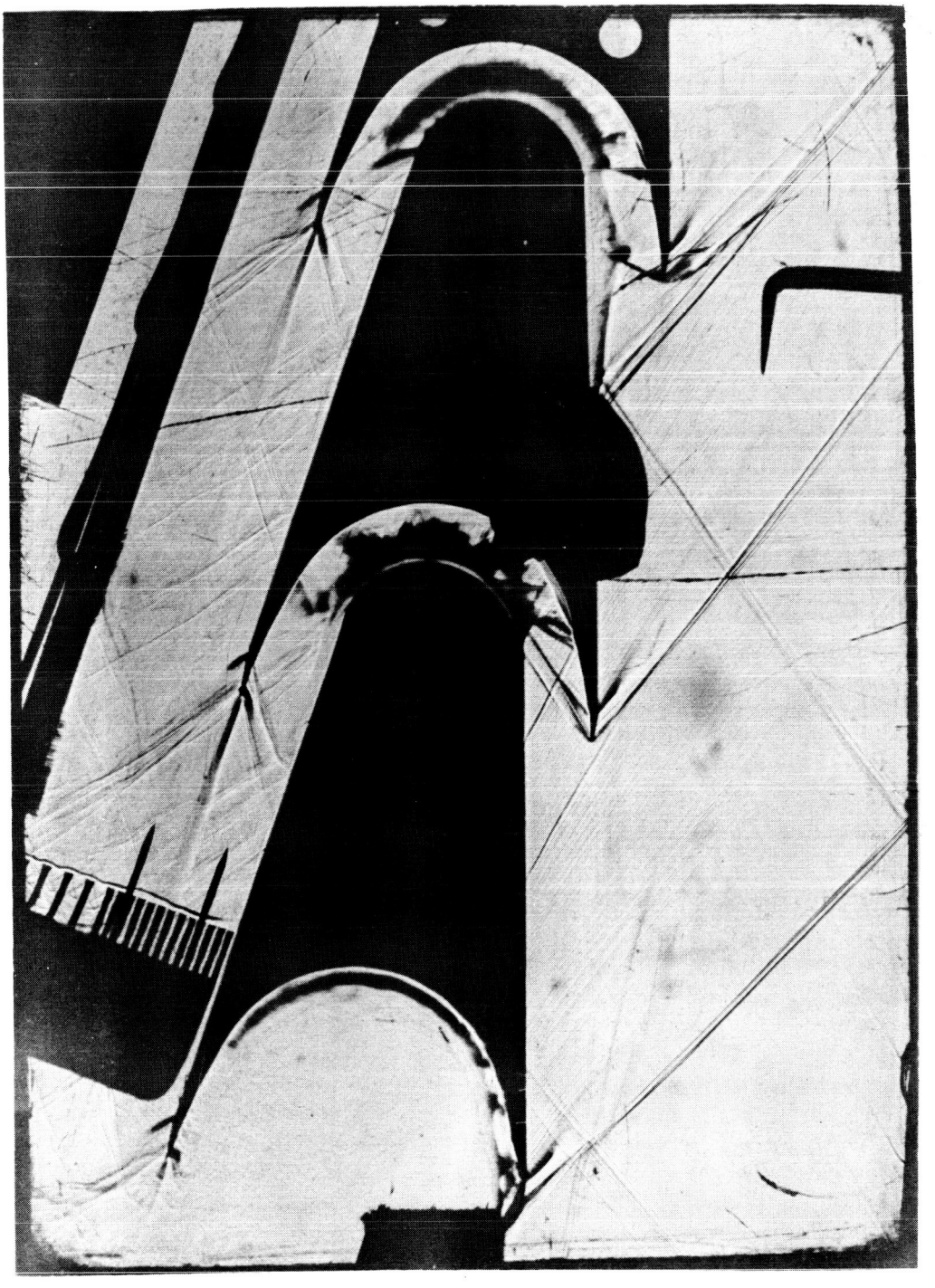


Figure 6.- Spanwise variation of section recovery factor of first passage.

UNCLASSIFIED



L-57-1617

Figure 7.- Schlieren photograph of full-contour blades at a floor angle of 5.2°. Rake is 1.500 inches from tunnel wall.

CONFIDENTIAL

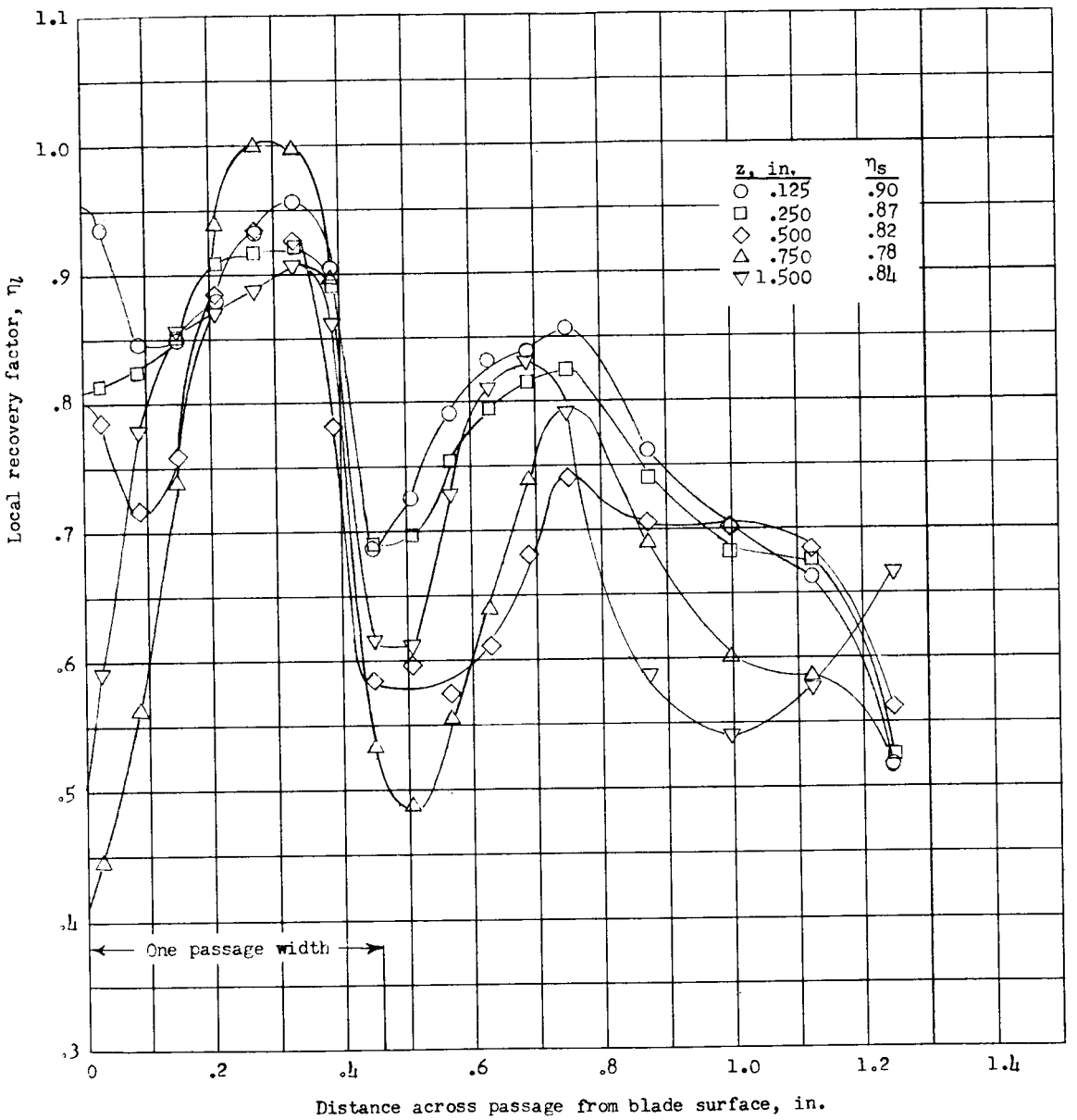
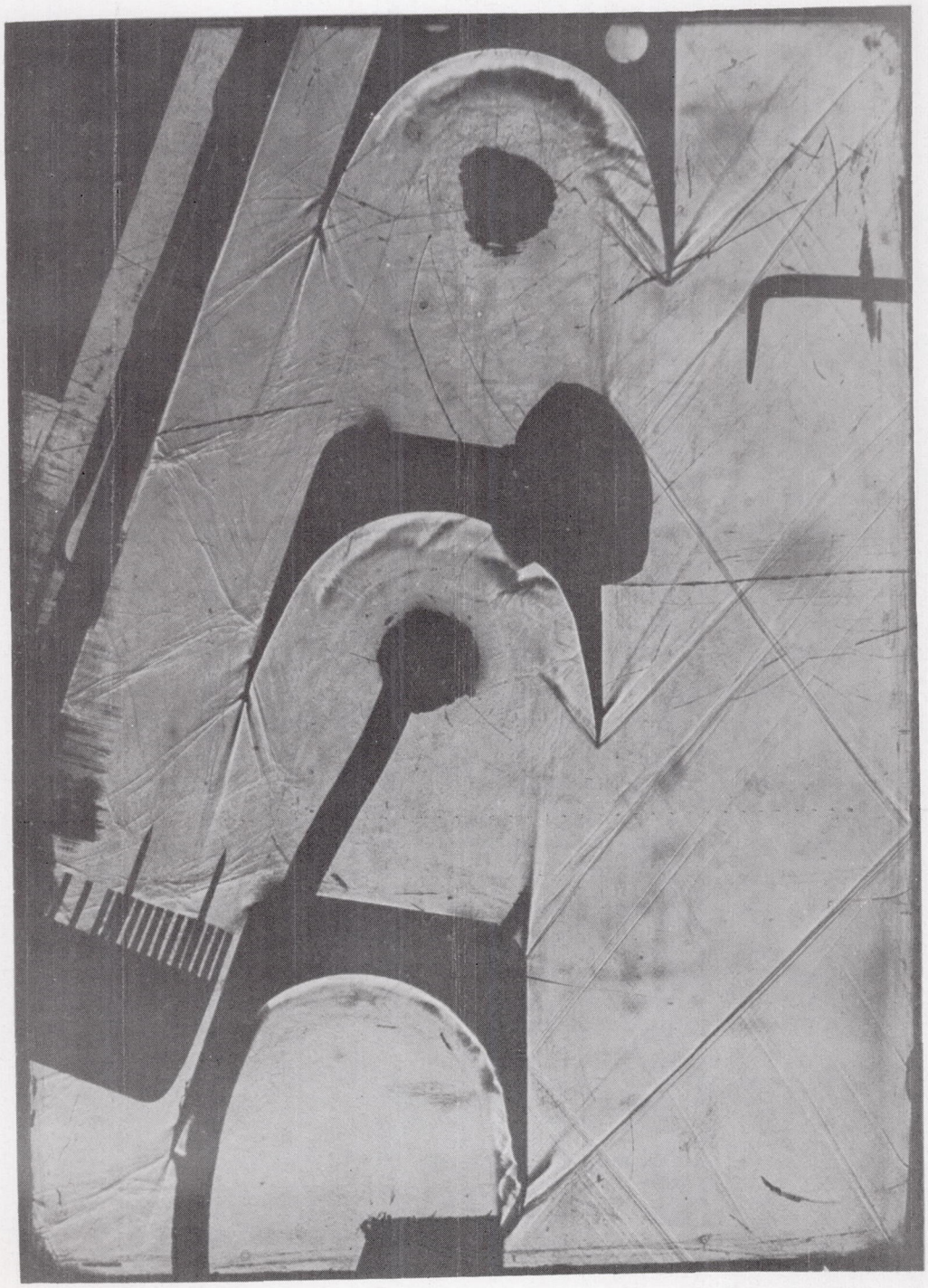


Figure 8.- Local recovery factor for full-contour blades at a floor angle of 5.2°. Only first passage started.

CONFIDENTIAL

UNCLASSIFIED



L-57-1618

Figure 9.- Schlieren photograph of free-streamline blades at a floor angle of 5.2°. Rake is 0.040 inch from tunnel wall.

CONFIDENTIAL

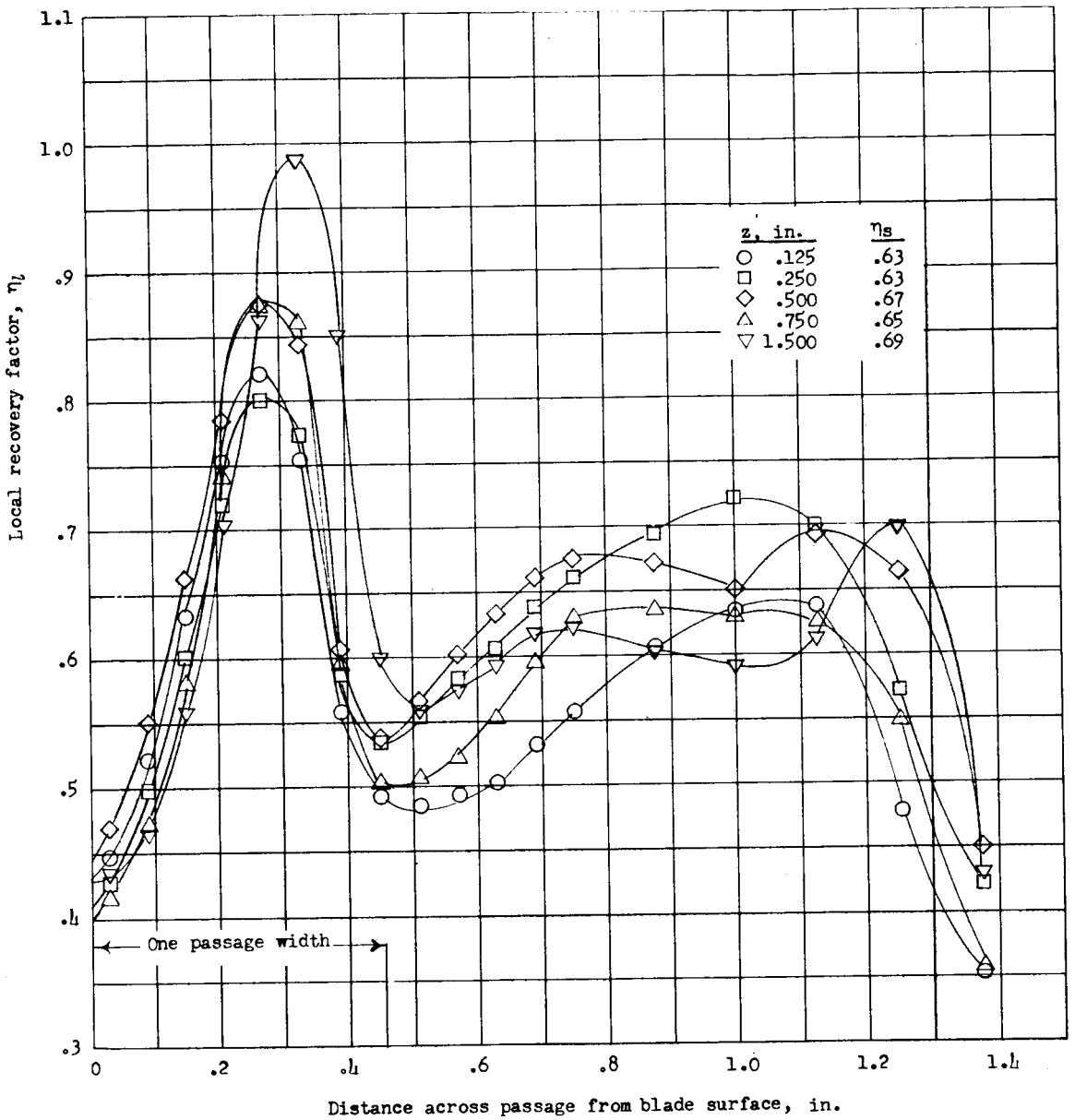


Figure 10.- Local recovery factor for free-streamline blades at a floor angle of 5.2°.

CONFIDENTIAL

UNCLASSIFIED

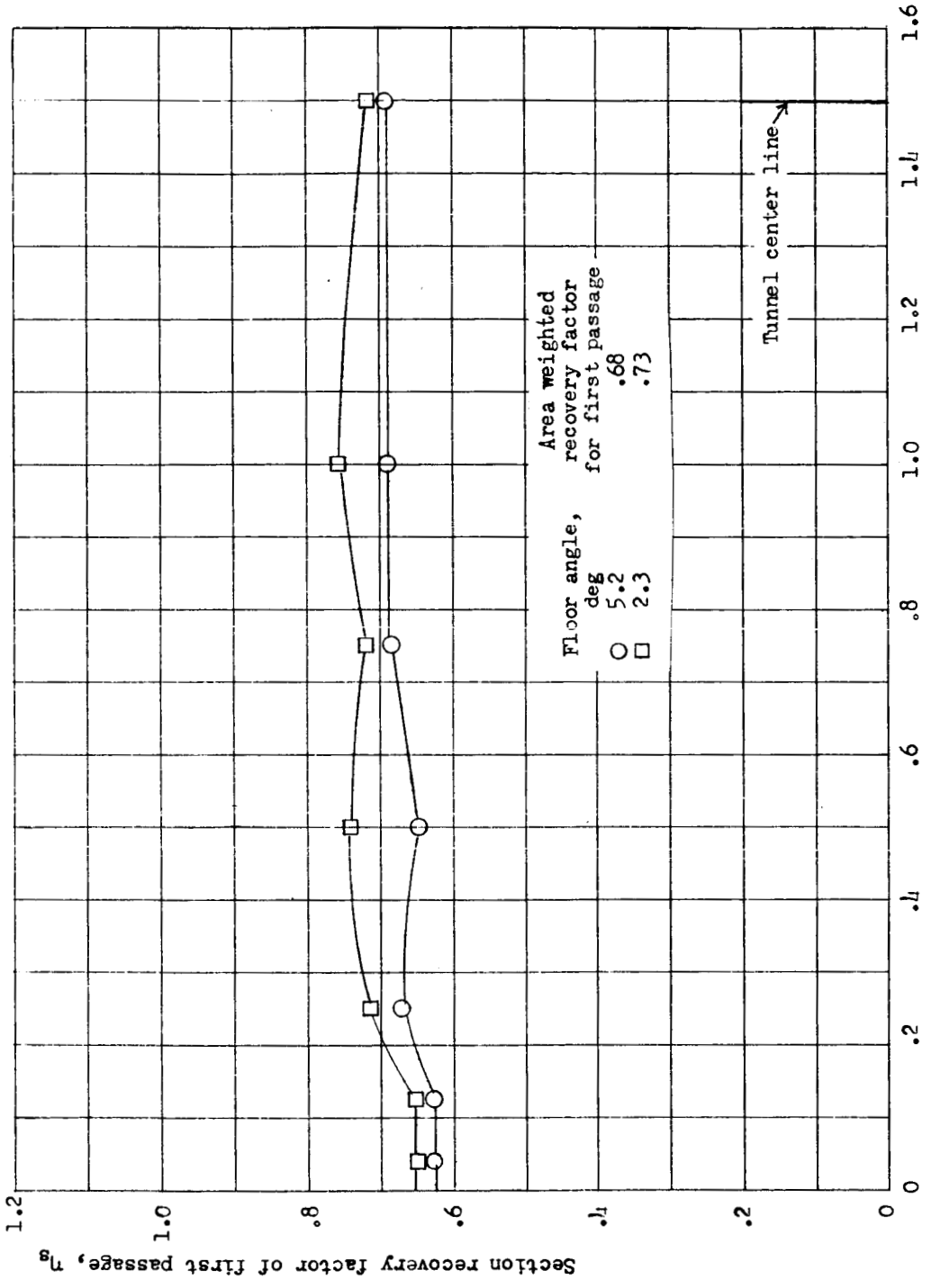
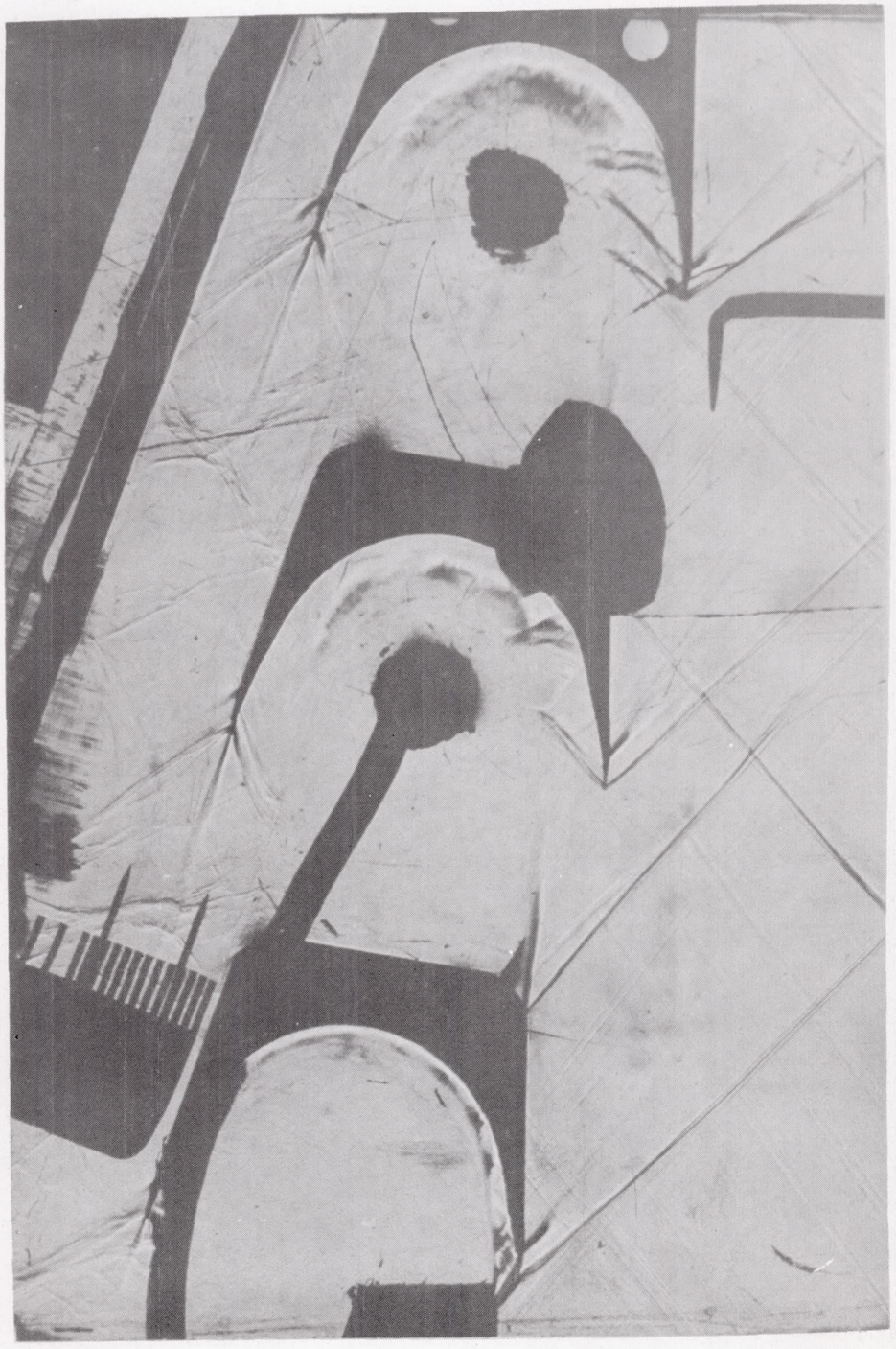


Figure 11.- Spanwise variation of section recovery factor of first passage.



L-57-1619

Figure 12.- Schlieren photograph of free-streamline blades at a floor angle of 2.3°. Rake is 0.040 inch from tunnel wall.

UNCLASSIFIED

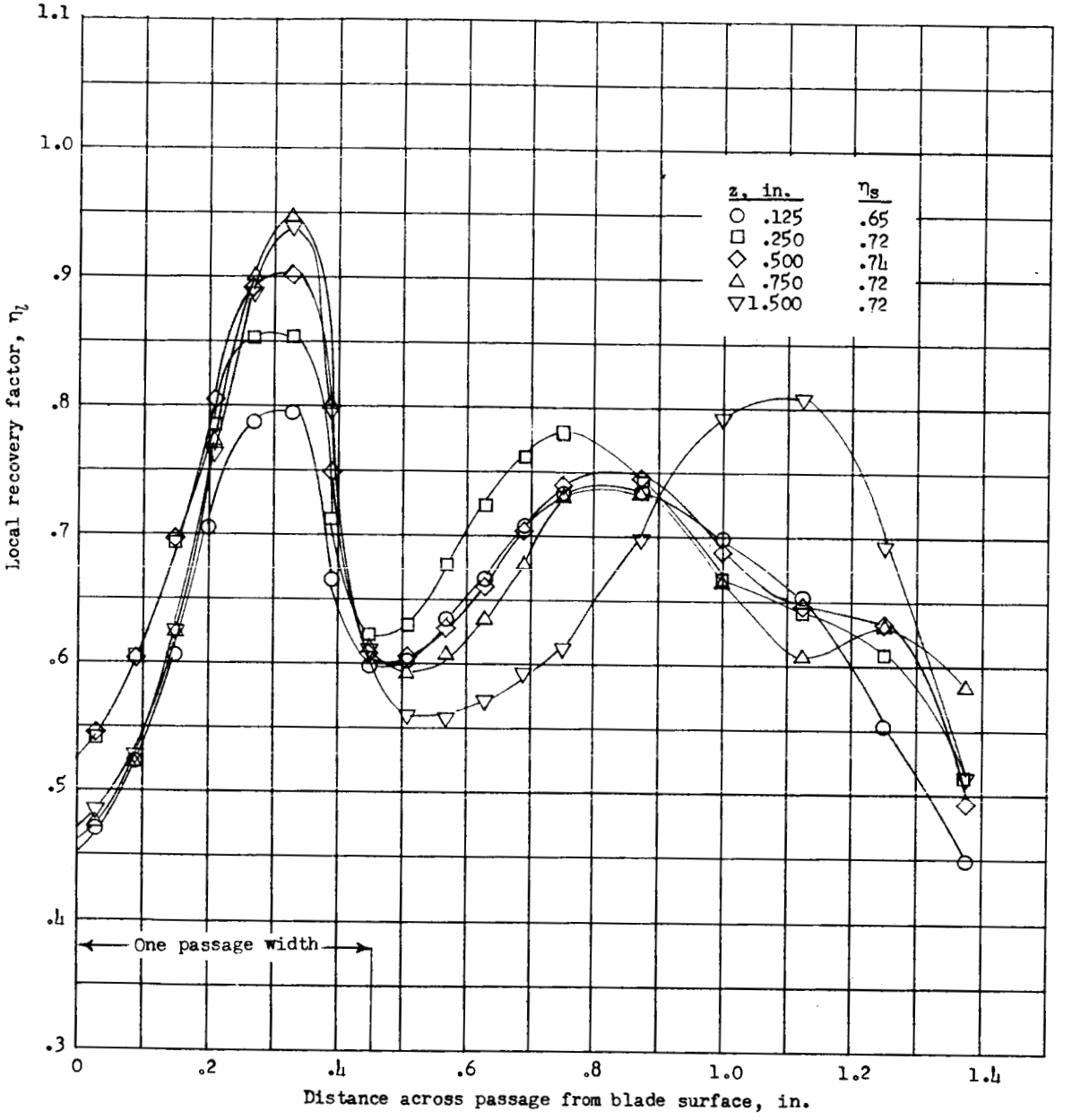


Figure 13.- Local recovery factor for free-streamline blade at a floor angle of 2.3°.

UNCLASSIFIED

UNCLASSIFIED